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Ultra-fast wavelength jumping and wavelength adjustment with low current using monolithically integrated FML for long reach UDWDM-PON

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Abstract: Ultra-fast wavelength jumping at optical network units (ONU) for access network with frequency modulated laser (FML) is demonstrated. This FML consists of Intra-cavity tunable phase section and filtering gain section. It provides a total of 4.2 nm tuning range with fast wavelength jumping (2.2 nm in 1 μs) and fast adjustment (1.3 nm in 1.8 ns), providing a candidate for the fast tuning ONU for coherent ultra-dense wavelength division multiplexing passive optical networks (UDWDM-PON).

Index Terms: Coherent communications, fiber optics systems, optical and other properties.

1. Introduction

The simple and low power consumption photonic device is mandatory in many application scenarios where a large concentration of transceivers is required, as in data centers and access systems [1], [2]. In particular, future access network based on long-reach ultra-dense wavelength division multiplexing passive optical networks (LRUDWDM-PON) takes advantages of wavelength selectivity and enhanced power budget [3]-[12], and provides capability of high splitting ratio, longer distance and compatibility with legacy infrastructure [4], [5], [10].

Photonic integration on both Silicon and InP is a way to achieve a lower footprint optical network unit (ONU) [5]. Recently, integrated components have been implemented for wavelength division multiplexing passive optical networks (WDM-PON) [13]-[18], and are being developed for UDWDM-PON [5], [19], [20].

The ONUs for ultra-dense next generation access network (NGAN) and latest next generation PON (NGPON) standard [21]-[25] are still using thermal effect at present [11], [13]. Traditionally, tuning the wavelength by thermal effect is slow [11]. During this tuning time, the connection is halted and the neighboring users can be interfered, this disadvantage would seriously impact the user's demand, especially on the network expected quality [3]. Hence, tuning time is desired to be as short as possible.

Interest in fast wavelength-tunable lasers is enhanced by their potential applications in a variety of multi wavelength network architectures [26]-[28]. Traditionally, photonics' wavelength tuning is used for network switching, and it presents a great performance for that application [13]. Several nano-seconds fast wavelength switching time is presented by three section Distributed bragg reflector (DBR) laser [28], [29], recently the wavelength switching time is less than 5 ns using

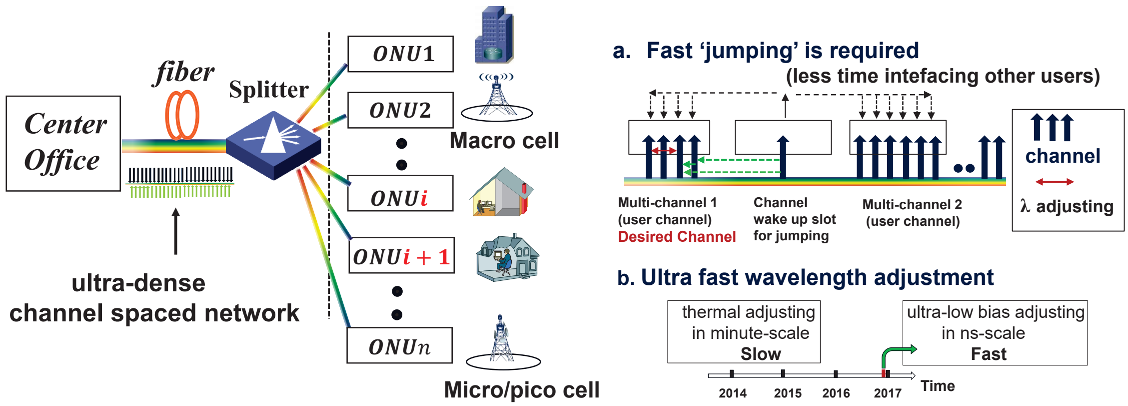

Fig. 1. UDWDM-PON schematic and its challenge at ONU.

sampled-grating DBR (SG-DBR) laser [30], and super structure grating DBR (SSG-DBR) laser has been developed to enlarge the tuning range, at the same time, with disadvantage of multi-section controlling dependent by thermal effects [31]. Hence, a simple and fast bias voltage/current controlling tunable laser is desired for UDWDM-PON ONU.

The wavelength tunable laser is not only useful for the switching network [13], but also useful for a colorless ONU [32], especially when it is integrated [5].

Here, we demonstrate, for the first time to the best of our knowledge, the fast wavelength jumping and adjustment with a monolithically integrated frequency modulating laser (FML) for coherent LRUDWDM-PON.

Fig. 1 shows the high level system concept. The optical trunk fiber is divided by a power splitter. When adding a user for ultra-dense access network (UDAN), firstly the wavelength is required to be waked up in a free wake-up slot as shown in Fig. 1; then this wavelength needs to be jumped to the desired channel; hence, this 'jumping' must be fast enough to avoid interfacing other users. Besides, after 'jumping', wavelength fine adjustment is also desired like tunable laser; however tunable laser for each ONU introduces a high cost implementation which maybe not suitable for the deployment of the ONU. Hence, we propose both 'jumping' and adjustment in less than one second by bias control with a low footprint integrated laser. Compared with the traditional thermal wavelength adjustment, from now on the wavelength adjustment could be operated with bias current in ns-scale by ultra-low bias current. The significant benefit of the wavelength adjustment under ultra-low bias condition (less than 7 mA) is that it presents high temperature independence, supporting future all optical green network for 5G implementation [33]-[35].

2. Characterization and assembly for FML

Due to basic semi-conductor material properties providing large optical index variation under modulation, FMLs can be ones of the most power efficient Electro-Optical converters [1]. Standard distributed feedback (DFB) lasers can realize large frequency deviations under modulations (chirp). However, they also have a large spurious amplitude modulation. The purpose of our work here was to reduce and eventually remove this amplitude modulation basing on a DFB phase-shifter modulation. The component design is schematically represented in Fig. 2(a). FML uses AlGaInAs quantum well and single active layer technology [36], consisting of gain section (GS) with 470 μm cavity and 75 μm grating phase adjustment section (PS).

Traditionally, integrated electro-absorption modulated laser (EML) consists of a DFB and an electro-absorption modulator (EAM), and the data is modulated in the EAM section with up to 100 Gb/s on-off-keying (OOK) signal or even more [36]; however, the DFB section serves as an optical carrier [36]. The integrated photonic device presented in [14], is a dual-driven electro-absorption modulated laser (DEML) which consists of a DFB and an EAM with dual electrical driven for DFB and EAM, respectively. Besides, a binary phase shift keying - EML (BPSK-EML) [25], consisting of a DFB, two phase shifter and 2 modulators, have attracted people's attention recently.

Here, the FML is designed for pure frequency modulation by modulating the PS [1]. Differently, it is desired to be modulated by the GS and take the benefit of fast tuning for wavelength jumping and adjustment. In order to avoid the electro-interfacing, a space between the two sections is kept. Traditionally, the PS is injected with DC bias and data; now, in order to modulate the GS, we put a 43 Ω resistor in series to provide an effective matched impedance [20]. However, regarding the PS, it is already injected a matching resistor from the manufactory as shown in Fig. 2(a). A temperature sensor is placed beside of the chip in order to reduce wavelength drifts, and the temperature is controlled at 298.15 K. After the assembly, it shows a 3-dB bandwidth (BW) of 9 GHz for the GS as shown in Fig. 2(b), and the 3-dB BW of the PS is around 13 GHz.

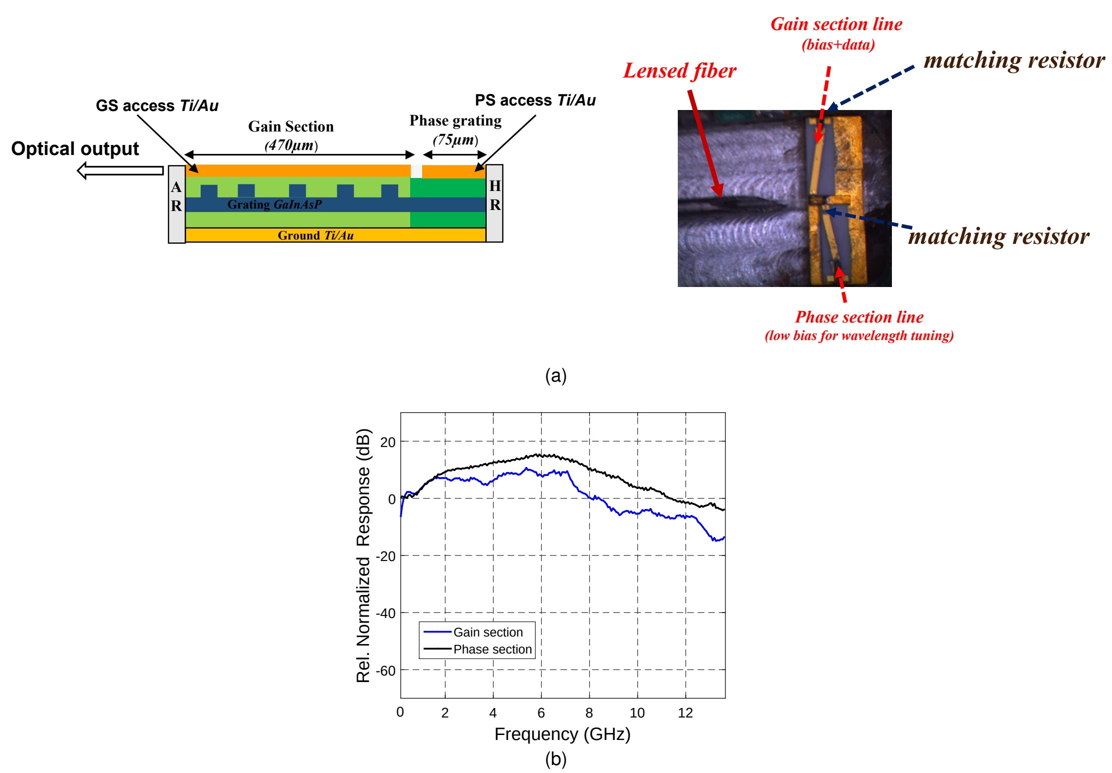

Fig. 2. (a) FML and assembly. (b) Normalized AM responses.

The wavelength at different bias conditions is shown in Fig. 3(a) and (b). Intra-cavity tunable phase section of 75 μm acts as DFB grating phase adjustment leading to different DFB mode positions inside its stop-band [1], which explains the phenomenon between Igs=30 mA and Igs=50 mA. There is 4.2 nm wavelength range from Igs=30 mA to Igs=130 mA as shown in Fig. 3(a), while for Fig. 3(b), with as low as 6 mA (from 1 mA to 7 mA), it can adjust 1.31 nm continuously. Unlike the DBR laser with multi-sections [26], [28]-[31], the FML with only two section provides enough jumping range, over 84 channels at 6.25 GHz spacing for ultra-dense access networks. Furthermore, less section chip provides the possibility for lower footprint and simplified ONU with less controls. For adjusting, varying the bias condition of PS can adjust the wavelength inside the desired channel quickly and avoiding the unwanted thermal effects.

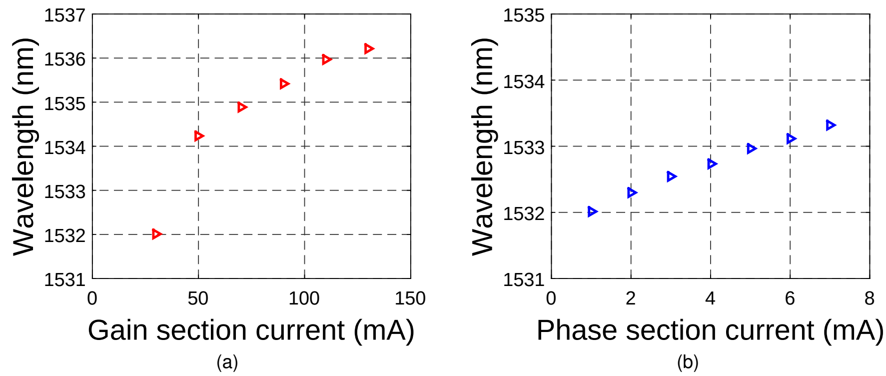

Fig. 3. (a) Laser wavelength versus gain section current, $I_{PS} = 1mA$. (b) Laser wavelength versus phase section current, $I_{GS} = 30mA$.

3. Proof of concept on fast jumping and adjustment

Dynamic characterization of the FML is carried out using the configuration of Fig. 4. Two types of experiments are performed, the first using a step pulse injecting GS to measure the jumping time between two lasing wavelengths, while the second is the same except injecting PS instead of GS. During the wavelength jumping measurement, the PS is kept at fixed bias condition to simplify the measurement. On the contrary, the GS is fixed for the wavelength adjustment measurement.

The resulting optical pulse output from the FML pass through an optical filter of 0.3 nm narrow bandwidth and the rise time is measured on a sampling oscilloscope with a 20 GHz photodiode (PD). As rise time, we refer to the time required for transition between 10% and 90% power at the desired wavelength [17], [31]. As a result, the different optical power presents the different wavelength for the wavelength-tuning-measurement [17]. The FML laser is operated at 298.15 K in pulsed mode with a 5 μs duration of switching pulse.

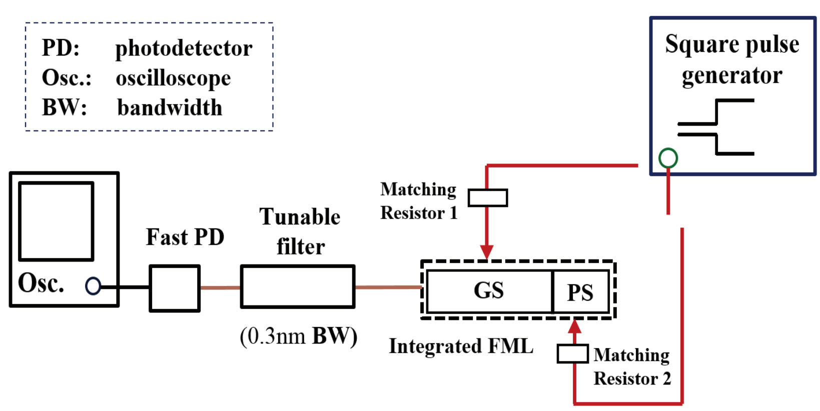

Fig. 4. Experimental setup for time calculation of wavelength jumping and adjusting.

Carrier effects occur within a few nanoseconds, however a temperature change is simultaneously produced by the heat generated by the current injection. Therefore, relatively slow wavelength variations also appear like the thermal drift as explained in Fig 5(a). The wavelength jumping time (T_{all}) is defined as the time taken for one wavelength (λ_1) to the allowable wavelength (λ_2) [17], hence the jumping time (T_{all}) mainly depends on the thermal drift time (T_t) if there is a thermal effect. However, when injecting with a few mApp signal, the tuning time mainly depends

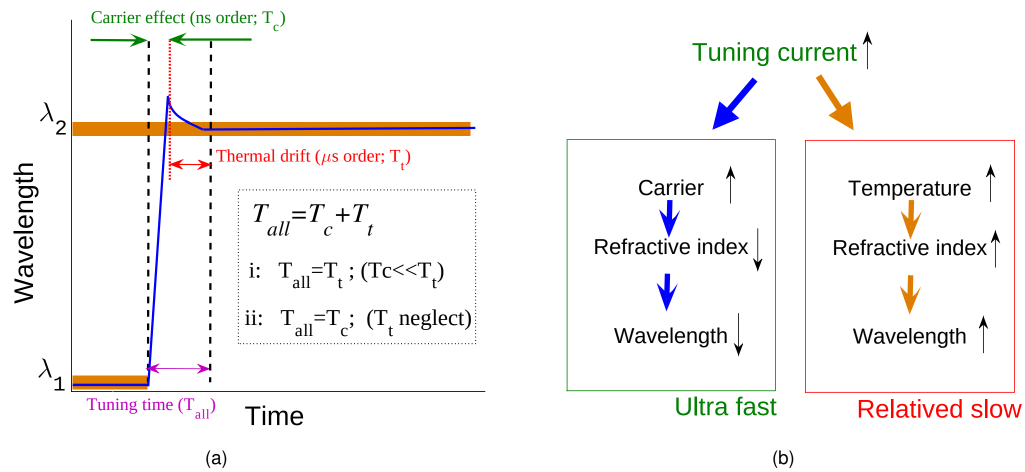

Fig. 5. (a) Diagram of wavelength tuning (from λ_1 to λ_2). (b) Explanation of phenomena.

on the time of carrier effect (T_c). Since the refractive index changes caused by carrier effects and the thermal effect are opposite, the relationship between wavelength and injected current is shown in Fig. 5(b).

For the wavelength jumping measurement, the bias for PS is kept at 1 mA, and the GS is 30 mA. However, the filter is pre-tuned to a second desired wavelength, here is 1534.24 nm, which corresponds to the case of Igs=50 mA. The amplitude of the pulse to the GS is selected at Ipp=20 mA, exactly equal the difference between the two gain section's conditions. Fig. 6(a) shows around 1 μs thermal drift time when jumping between the two wavelengths, the carrier effect time is 2.7 ns as shown in Fig. 6(b). Hence, Unlike the traditional thermal effects in several ms-scale, here the wavelength jumping time is only 1 μs, due to the temperature sensor placed as closer as possible. Compared with the traditional temperature controlled wavelength jumping, here the current controlling method presents benefit for the rapid optical networks.

At the other side, for the PS wavelength adjustment test, the GS is fixed at 30 mA, the bias for PS is 1 mA, and the filter is set at 1533.32 nm now, which corresponds to the case of Ips=7 mA. Then after adding Ipp=6 mA of square signal to the PS, the emitted wavelength is passed by the filter when the pulse is at the upper level. The wavelength adjustment is applied with the low signal amplitude and ultra-low bias makes the thermal effects negligible as shown in Fig. 6(c). Fig. 6(d) shows the carrier effect which corresponds to the tuning time in 1.8 ns only. It is a strong proof of concept for ultra fast tuning for the near future optical networks.

4. Performances

Here, 5 Gb/s 2^{18} non-return-zero (NRZ) binary sequences are generated and modulate the GS after adding matching resistor. After 110 km standard single mode fiber (SSMF) distribution, the amplitude-shift keying (ASK) signal is coherently detected using heterodyne detection with a single PD at the center office (CO) as shown in Fig. 7.

The GS signal amplitude is as low as 10 mA, and as in previous section, the bias condition are Igs=30 mA, Ips=1 mA for $user_1$, and Igs=50 mA, Ips=1 mA for $user_2$, corresponding to the same condition of wavelength jumping. With the purpose of maintaining the injecting power into the remote node (RN) like the $user_1$, a proper optical attenuator is introduced for the $user_2$ test.

For $user_1$, at the standard forward error correction (FEC) level of bit error ratio (BER) = 1.0×10^{-3} [9], [10], the sensitivity is -31.3 dBm (back-to-back, BtB), and -29.4 dBm (110 km). There is 1.9 dB penalty between BtB and fiber transmission as shown in Fig. 8.

For $user_2$, the sensitivity now reaches -32.8 dBm and -30.6 dBm for BtB and 110 km fiber

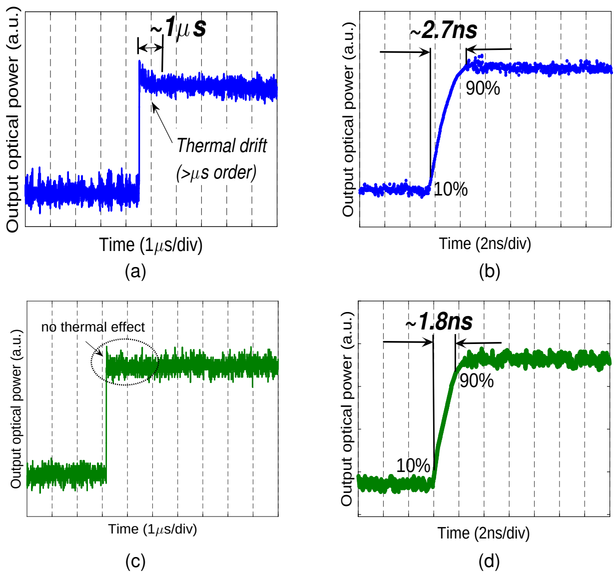

Fig. 6. (a) Oscilloscope traces showing thermal drift time (GS). (b) carrier effect time for wavelength jumping (GS). (c) Oscilloscope traces showing thermal drift time (PS). (d) carrier effect time for wavelength adjustment (PS).

transmission, respectively. Compared with $user_1$, $user_2$ has 1.5 dB, 1.2 dB sensitivity improvement for BtB and fiber transmission. An eye diagram with BER=10^{-4} level is shown in the inset of Fig. 8. The results show the successfully validated transmission for the users located at the fast jumped channel, which support the previous proposal for the future mass deployment of the UDWDM-PON.

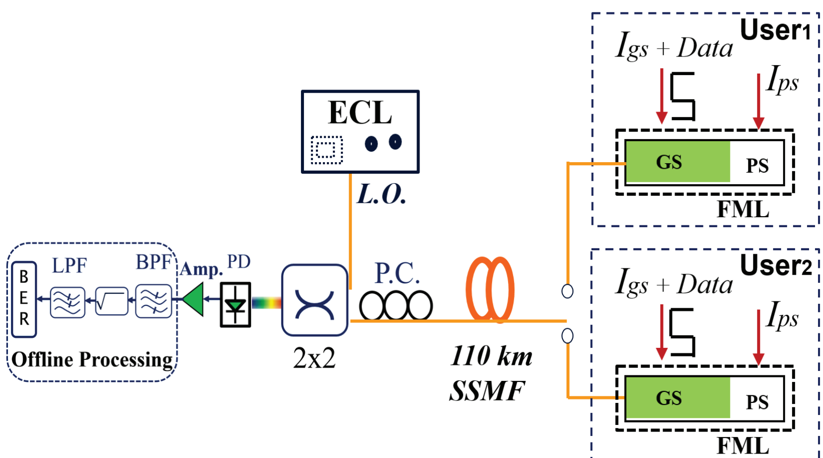

Fig. 7. Integrated FML transmission experimental setup.

5. Conclusions

We have demonstrated an ultra-fast λ-tuning integrated laser, directly modulated at 5 Gb/s for UDWDM-PON. Traditionally, it is obvious that reconfiguring the wavelength of the laser at the

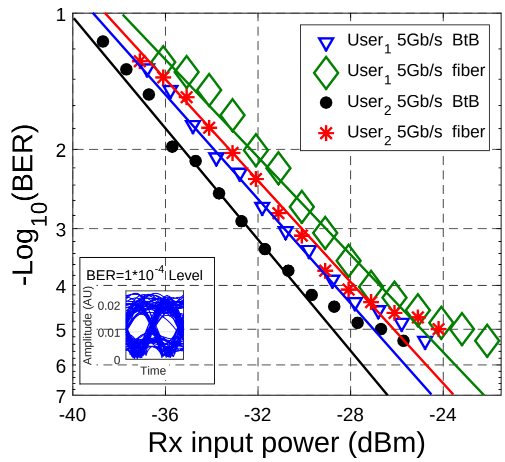

Fig. 8. BER versus received input power for $user_1$ and $user_2$.

ONU is slow with temperature, as the wavelength's drift by temperature would interfere other ultra-dense channels. Based on this, in this paper, wavelength jumping over 84 UDWDM channels in μs-scale and ns-scale by current controlling is presented, providing much better performance than the traditional effect in serveral seconds scale for conventional thermal tuned DFB. Furthermore, after jumping the required channel, the wavelength adjustment shows an ultra fast wavelength tuning with ns-scale, crossing over 26 UDWDM channels within 6 mApp only; this avoids the unwanted thermal affects, opening a way to deployment for next generation dynamic ultra dense WDM access networks.

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